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ORIGINAL RESEARCH

Physico-chemical attributes of a Cambisol under pasture managed with annual burns after sugarcane vinasse application

Thadeu Rodrigues de Melo[1] · Rogério Resende Martins Ferreira[2] · Deisi Navroski[1] · Clarissa Tieme Matsuda Feltran[1] · João Tavares Filho[1]

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Abstract

Purpose Sugarcane vinasse is generated in large amounts and can be utilized to improve soil attributes, especially in areas degraded by burns. The aim of the present study was to evaluate the effects of sugarcane vinasse on physico-chemical attributes of a Cambisol managed via annual burns.

Methods Soil samples were collected from an annually burned area under pasture and used in an experiment in pots to evaluate the effects of dosages of vinasse (0, 18.8, 37.5, 56.3, 75.0, 112.5, and 150.0 m^3 ha^{-1}) on water-dispersible clay, pH_{H_2O}, organic matter, K^+, $Ca^{2+} + Mg^{2+}$, and $K^+/(Ca^{2+} + Mg^{2+})$.

Results The results showed that vinasse application reduces water-dispersible clay, does not alter pH_{H_2O}, and increases organic matter, K^+, $Ca^{2+} + Mg^{2+}$, and $K^+/(Ca^{2+} + Mg^{2+})$. The water-dispersible clay was reduced by the formation of bonds with organic matter, which overlapped the repulsive forces intensified by the increment of $K^+/(Ca^{2+} + Mg^{2+})$. The estimated vinasse dosage that provided the minimum water-dispersible clay (69 g kg^{-1}) was 110 m^3 ha^{-1}.

Conclusions Vinasse can be applied to improve the physico-chemical attributes of soils degraded by annual burns.

Keyword Organic fertilization · Soil flocculation · Sustainability · Soil restoration

Introduction

The microregion of São João Del Rei, in the State of Minas Gerais, is characterized by the predominance of small rural properties, mainly used for dairy cattle. For feeding of the animals, pastures of low productivity are used, which implies in the necessity of supplementation, commonly carried out by the cultivation of sugarcane (Pelegrini 2010).

The pastures are burned mainly during the dry period, between June and August, to clear areas, burn residues, control shrub growth, reduce the incidence of invasive plants, and eliminate pests and diseases (Horta et al. 2009). However, this practice reduces the organic matter content and, consequently, leads to soil degradation (Ferreira et al. 2012).

The sugarcane is also used in the artisanal manufacture of sugarcane spirit, with vinasse being the main residue generated during ethanol distillation; For each ton of sugarcane processed, 780 L of vinasse are generated (Sebrae 2001). Applying sugarcane vinasse to the soil can help attenuate soil degradation and improve vegetal development (Canellas et al. 2003).

Recently, there have been many discussions on the progress of wastewater reuse globally to protect the environment and achieve sustainable resources (Wu et al. 2013). Vinasse can be reused as a fertilizer, providing nutrients to plants, mainly potassium, nitrogen, and phosphorous (Moraes et al. 2015; Dotaniya et al. 2016). An understanding of the effects of vinasse on soil physico-chemical attributes is valuable, especially in degraded areas, to maximize the efficiency of soil restoration and increase family income.

The high levels of potassium in vinasse and other sugarcane residues (Kumar and Chopra 2016) can increase water-dispersible clay and cause physical degradation due to the

✉ Deisi Navroski
deisinavroski@gmail.com

1 Department of Agronomy, Universidade Estadual de Londrina [State University of Londrina] (UEL), Celso Garcia Cid Highway, s/n, 10011, CEP 86057-970 Londrina, PR, Brazil

2 Empresa Brasileira de Pesquisa Agropecuária [Brazilian Agricultural Research Corporation], EMBRAPA, Rio Branco, AC, Brazil

increments in electrostatic repulsion between the clays (Marchuk and Rengasamy 2011). However, organic matter can favor the flocculation and aggregation of clays, thus improving soil structural stability (Bronick and Lal 2005). Therefore, the predominance of clay dispersion or flocculation will depend on the capacity of one of these two processes to overlap the other.

The hypothesis of the present study is that vinasse will change the content of water-dispersible clay, depending on the chemical changes resulting from the formation of bonds by organic molecules and the electrostatic repulsion by K^+ increment. The aim of the present study was to evaluate the effects of sugarcane vinasse on physico-chemical attributes of a Cambisol managed with annual burns.

Materials and methods

Site and soil characterization

This study was performed in pots containing soil from pastures located in the hydrographic basin of Alto Rio Grande, municipality of Nazareno, Minas Gerais, Brazil, located at 21°22′S and 44°61′W with an average elevation of 935 m (Fig. 1). The regional climate is high-elevation tropical, with cold, dry winters and hot, humid summers, and is classified as Cwa in the Köppen system. The average annual temperature ranges from 18 to 19 °C, and the total annual rainfall ranges from 1200 to 1500 mm.

The soil is classified as a Cambisol based on the International Soil Classification System (IUSS Working Group 2015) (Brazilian classification: Cambissolo Háplico; US Department of Agriculture classification: Inceptisol), and originates from pelitic rocks and quartzite (Horta et al. 2009), under native pasture (*Diandrostachya chrysotrix*, *Paspalum plicatulum*, and *Andropogon leucostachys*). The soil was managed using annual burns to clear vegetation.

A total of 40 soil samples were collected 30 days after the annual burn from a depth of 0–20 cm. In the laboratory, the samples were mixed and sieved (2 mm). The soil physico-chemical attributes were determined (Table 1), and the experimental pots were filled.

Table 1 Physico-chemical attributes of the Cambisol under pasture managed with annual burns collected at a depth of 0–20 cm

Attribute	Value
Clay (g kg^{-1})[a]	380
Silt (g kg^{-1})[a]	250
Sand (g kg^{-1})[a]	370
Silt/clay	0.67
Water-dispersible clay (g kg^{-1})[b]	91.0
Particle density (Mg m^{-3})[c]	2.67
pH_{H_2O}[d]	4.5
CEC_{pH7} ($cmol_c$ dm^{-3})[e]	6.5
Ca^{2+}+Mg^{2+} ($cmol_c$ dm^{-3})[e]	0.83
K^+ ($cmol_c$ dm^{-3})[e]	0.006
Organic matter (g kg^{-1})[f]	8.0

[a]Pipe method with NaOH (1 mol L^{-1}): 16 h of agitation, 200 rpm

[b]Pipe method without dispersant: 3 h of agitation, 30 rpm

[c]Determined by the volumetric balloon with ethanol method

[d]1:2.5 soil:water ratio (v:v)

[e]*CEC* cation exchange capacity (H + Al^{3+} + Ca^{2+} + Mg^{2+} + K^+). H + Al^{3+} determined by potentiometry after equilibrium with SMP solution. Ca^{2+} + Mg^{2+} determined after exchange with KCl (1 mol L^{-1}). K^+ extracted by Mehlich-1

[f]Oxidation with $K_2Cr_2O_7$ in sulfuric medium

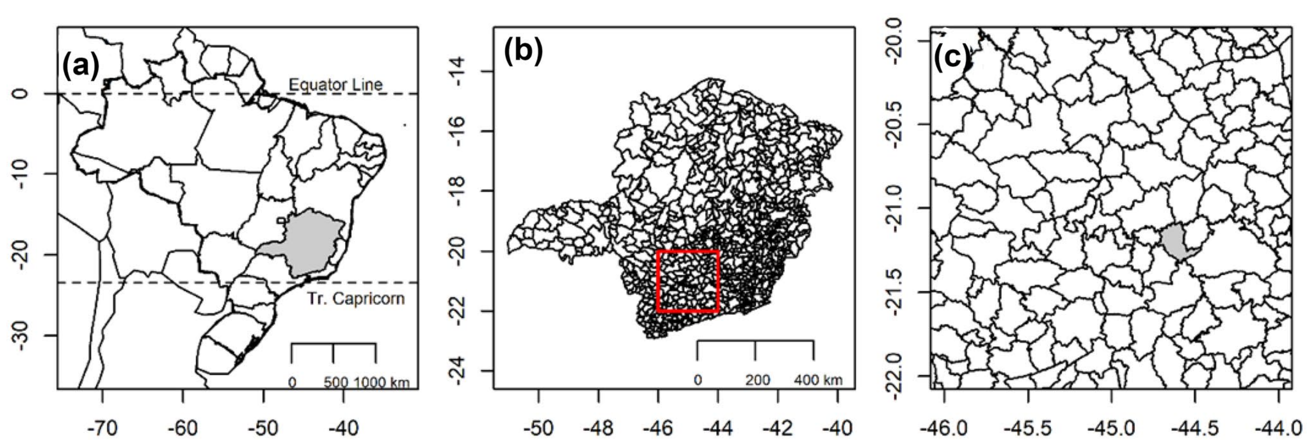


Fig. 1 Location of Minas Gerais State, Brazil (**a**), detail of Minas Gerais' municipalities (**b**) and Nazareno municipality (**c**)

Establishment and conduction of the experiment

The pots had inner linings composed of plastic bags, and were filled with 2.0 kg of 2 mm sieved soil from the composite sample (composed of a mix of the 40 discrete samples collected in the area). A fully randomized experimental design was used, with seven treatments and three replications. The treatments consisted of different dosages of vinasse [0 (control), 18.8, 37.5, 56.3, 75.0, 112.5, and 150.0 m^3 ha^{-1}]. The characterization of the vinasse is shown in Table 2. After vinasse application, the soil was watered to maximum retention capacity and incubated, leaving an opening for gaseous exchange during the 60-day incubation period.

The maximum water retention capacity was determined by the filling of volumetric rings with soil with subsequent saturation and gravitational drainage until constant weight. After incubation, the pots were opened and three replicates were collected per treatment.

The pH_{H_2O} and exchangeable K^+ and Ca^{2+} + Mg^{2+}, organic matter and water-dispersible clay were determined according to the method of Embrapa (1997) and Pavan et al. (1992). The pH was measured in a 1:2.5 soil:water ratio (v:v), K^+ was measured after extraction with Mehlich-1 and quantified in a flame spectrophotometer, and Ca^{2+} + Mg^{2+} were exchanged by KCl 1 mol L^{-1} and quantified by titration with EDTA-Na_2. Organic carbon was determined by oxidation with $K_2Cr_2O_7$ in sulfuric medium and multiplied by the Van Bemmelen factor of 1.724 to obtain the organic matter content. The water-dispersible clay was evaluated with the pipette method, based on Stoke's Law, on samples agitated using a laboratory orbital stirring table (Tecnal TE-145) at 30 rpm for 3 h.

Table 2 Characterization of the vinasse used in the present study

Attribute	Value
pH[a]	3.80
OM (kg m^{-3})[b]	19.20
N (kg m^{-3})[c]	1.20
P_2O_5 (kg m^{-3})[d]	0.17
K_2O (kg m^{-3})[d]	2.80
CaO (kg m^{-3})[d]	2.02
MgO (kg m^{-3})[d]	0.70

[a]Measured directly on the vinasse

[b] Oxidation with $K_2Cr_2O_7$ in sulfuric medium

[c]Determined by the Kjeldahl method

[d]Determined after nitropercloric digestion by spectrophotometry (P_2O_5), flame photometry (K_2O) and atomic absorption (CaO and MgO)

Statistical analyses

The ANOVA's assumptions of normality and homoscedasticity were tested using the Shapiro–Wilk and Cochran's tests, respectively. The results were evaluated by ANOVA (*F* test), and for low *p* values (≤ 0.05), the best regression model was adjusted. The relationship between chemical attributes and water-dispersible clay was determined with linear regression models. The R software (R version 3.3.2) was used for data analysis and creation of figures.

Results and discussion

The effects of vinasse on soil chemical attributes are shown in Fig. 2.

None of the applied doses exceeds the critical K content in the soil, which is 5% of the CEC_{pH7} plus the annual extraction of the plants, delimited in the Normative Deliberation of the State Council of Minas Gerais (Minas Gerais 2011), since at the highest dose, soil presented only 0.5% of saturation per K (data not shown).

The pH strongly affects water-dispersible clay and, consequently, soil structural stability. Changes in pH can increase the net charge of the clay surface and intensify the repulsive forces, favoring dispersion (Plaza et al. 2015). However, in the present study, vinasse application did not affect soil pH (Fig. 2a), despite changes in this attribute having been reported previously (Silva and Ribeiro 1998; Ribeiro et al. 2012).

The increment in pH by the vinasse application is associated to the higher biochemical demand for oxygen, which makes the H^+ the final acceptor of electrons, raising the pH (Moran-Salazar et al. 2016), even with the low pH of the vinasse (Ribeiro et al. 2012). As the pH increment is dependent on biological activity, the continuous use of fire for pasture management may have reduced the microbial population, preventing pH changes.

The soil organic matter increased linearly with vinasse application (Fig. 2b), corroborating the study of Canellas et al. (2003), that reported an increase in the humic and fulvic acids in an Inceptisol caused by vinasse addition during a long period.

Organic molecules can disperse or flocculate soil clays. Some organic compounds such as proteins (Nelson et al. 1999) and low molecular weight organic compounds (Nguyen et al. 2013) can act as clay dispersants. However, organic molecules, such as the aliphatic ones (Nelson et al. 1999), can also bind two or more clays together, which increases aggregate stability (Bronick and Lal 2005)

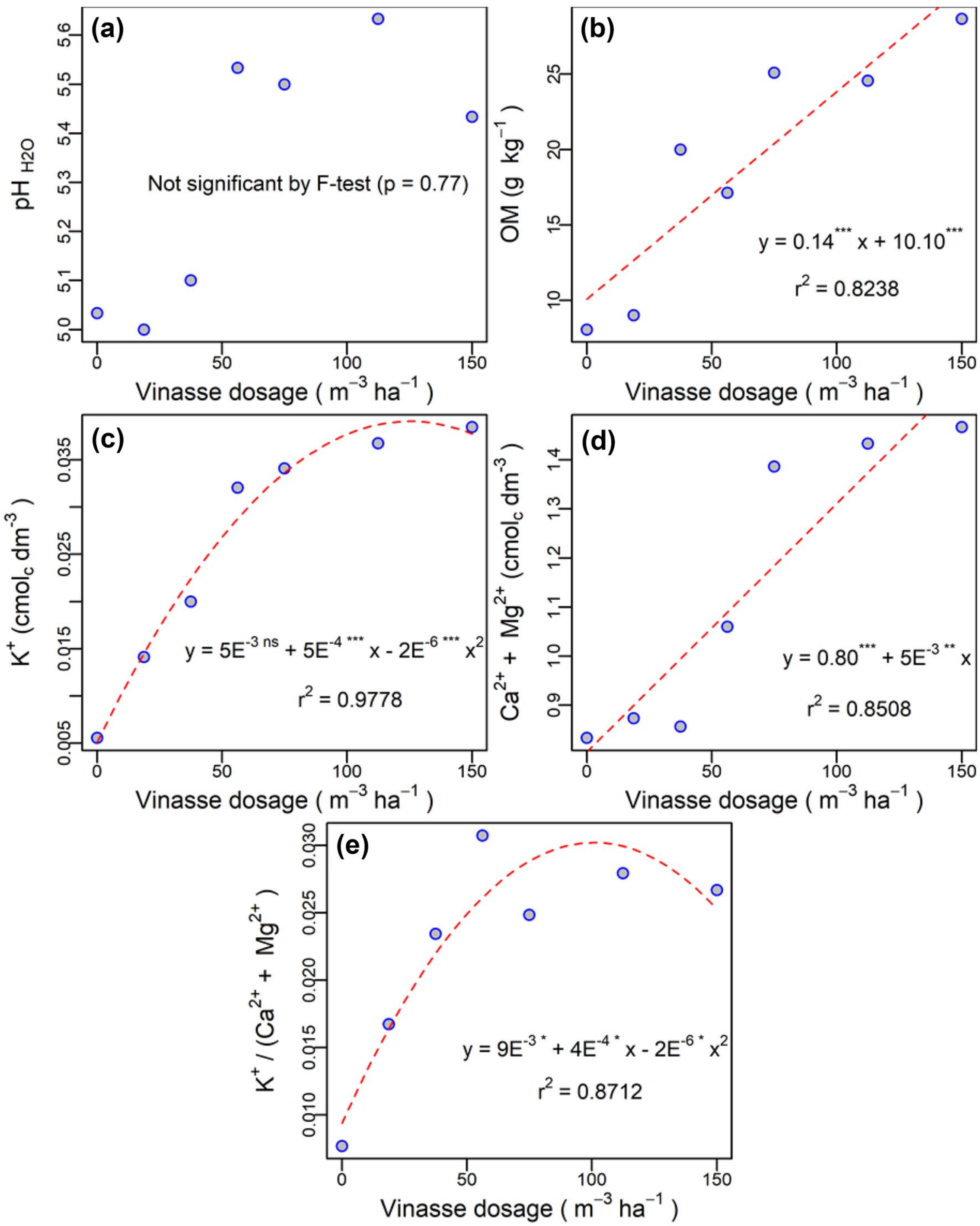


Fig. 2 Results from *F* test and regression model for the evaluated attributes in a Cambisol fertilized with vinasse

and clay flocculation (Tavares Filho et al. 2014). In addition, vinasse increases microbiological activity, which can release exudates and increase soil aggregation (Bronick and Lal 2005). The increment in total soil organic matter content following vinasse application linearly reduced the water-dispersible clay (Fig. 3a).

In electronegative soils, monovalent cations increase the water-dispersible clay, while bivalent cations favor flocculation (Melo et al. 2016). Vinasse dosages increased K^+, $Ca^{2+} + Mg^{2+}$, and $K^+/(Ca^{2+} + Mg^{2+})$ values (Fig. 2c–e). It is expected that samples with greater values of $K^+/(Ca^{2+} + Mg^{2+})$ become more dispersed than those with

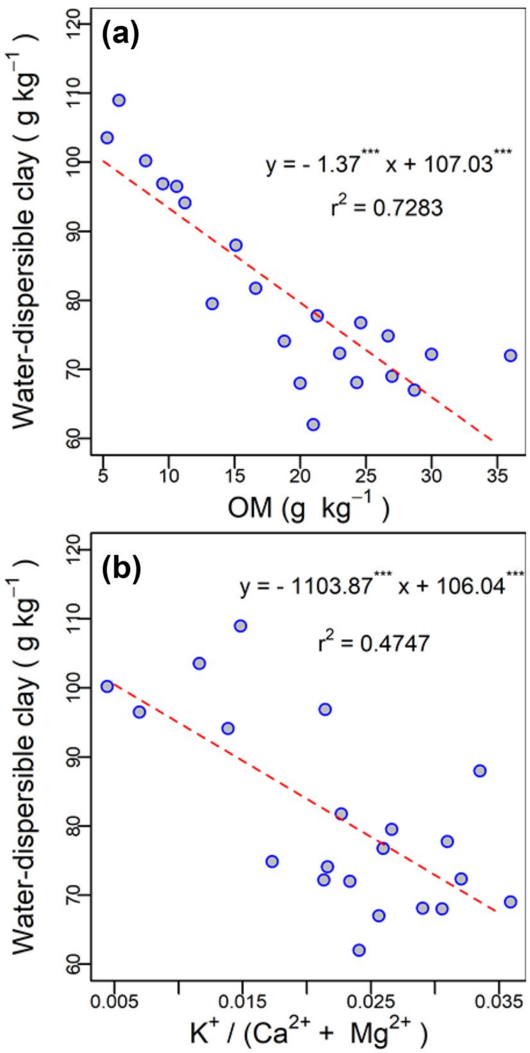


Fig. 3 Relationship between water-dispersible clay and total soil organic matter content (**a**) and the ratio of monovalent/bivalent cations (**b**) in a Cambisol fertilized with vinasse

lesser values. Dispersion is intensified in soils with higher monovalent cation concentration due to thickening of the electric double layer (Mahanta et al. 2012), smaller zeta potential neutralization when compared to bivalent cations (Marchuk and Rengasamy 2011), and smaller interaction with soil organic molecules (Setia et al. 2013), which reduces the clay-organic matter bonds (Roychand and Marschner 2014).

A negative linear correlation was obtained between $K^+/(Ca^{2+} + Mg^{2+})$ and water-dispersible clay, which was in contrast to our expectations (Fig. 3b). The statistical significance of this model (Fig. 3b) is probably owing to the correlation between $K^+/(Ca^{2+} + Mg^{2+})$ and organic matter when vinasse is applied, with the flocculent effects caused by clay-organic matter binding overlapping the electrostatic repulsive forces caused by the increment in $K^+/(Ca^{2+} + Mg^{2+})$ (Fig. 4).

Prado et al. (2014) reported a reduction in water-dispersible clay in an Oxisol, with organic matter and K^+ increment, corroborating the results of the present study.

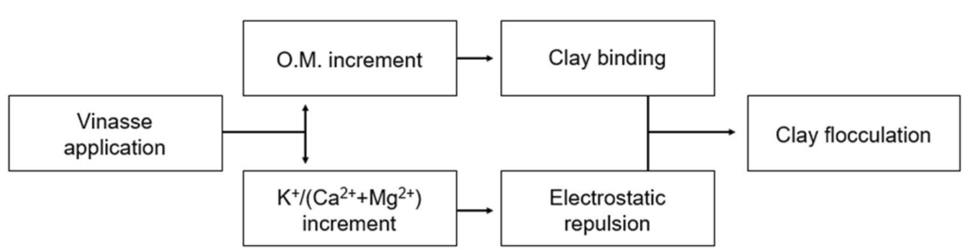
The remarkable presence of aluminum sesquioxides in this Cambisol (Horta et al. 2009) and its strong interaction with organic compounds (Heckman et al. 2011) explains the association of these clay-sized minerals to organic vinasse compounds reducing water-dispersible clays.

Some studies reported in the literature corroborates the idea that the effects of organic compounds after vinasse application overlap the repulsion caused by K^+ increments in the soil exchange complex. Ribeiro et al. (2013) observed that vinasse application increased the amount of energy necessary to disperse the aggregates by reducing the disaggregation and dispersion constants in an Oxisol and an Ultisol. Vicente et al. (2012) observed a significant correlation between total organic carbon and aggregation indices in different soils when vinasse was added. So, vinasse can be applied to improve the physico-chemical attributes of soils degraded by annual burns.

The model from the data in Fig. 5 estimates that the minimum clay dispersion (69 g kg^{-1}) occurs when 110 m^3 ha^{-1} vinasse is applied. Although the second-degree model fits better, there was no indication of dosages greater than 110 m^3 ha^{-1} increasing dispersion. The absence of response after this dose probably occurred due to the saturation of part of the dispersed clay fraction with phosphate and organic molecules of low molecular weight, which intensify the electronegative potential of the particles, without allowing the formation of bonds and consequently their flocculation (Nguyen et al. 2013).

As the dispersed clay content is extremely dependent on the method used, the interpretation of the suitability for the results is difficult. However, it is known that the closer to

Fig. 4 Organogram of the attributes altered by vinasse application and their effect on the net water-dispersible clay decrease



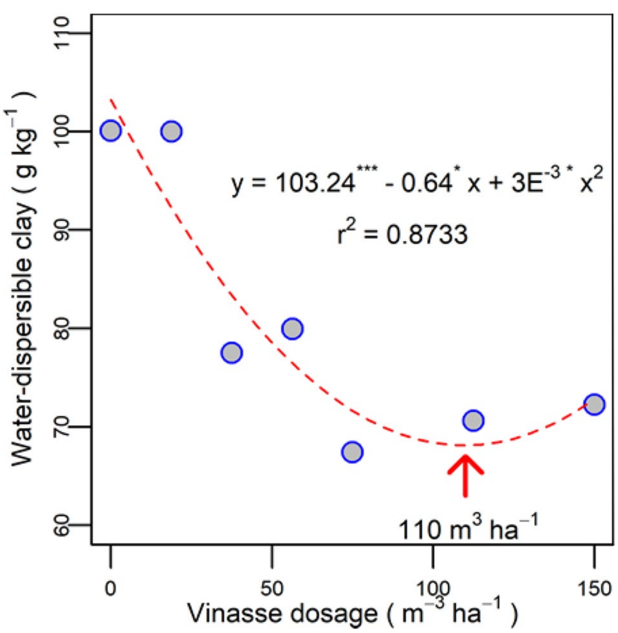


Fig. 5 Water-dispersible clay in function of the applied vinasse dosage

zero, the lower the transport potential and the loss of particles of the clay fraction. With the reduction of clay dispersion, it is expected a lower potential transport of contaminants associated with these particles to water bodies (Martin et al. 2016). In addition, soil structural improvement may occur due to less clogging of pores by the reorganization of the dispersed clay (Spera et al. 2008).

Conclusion

Our results showed that the vinasse can attenuate the chemical and physical degradation imposed by the management of pastures with fire. Increment on cations concentration (K^+ and $Ca^{2+} + Mg^{2+}$) could be observed, suggesting a higher availability to plants. However, the pH of the soil, initially at 4.5, could not be neutralized with the vinasse application, probably due to the low biological activity caused by the constant use of fire. Initially, we believed that increasing the $K^+/(Ca^{2+} + Mg^{2+})$ ratio by the vinasse application could induce the increase of water-dispersible clay content, but the formation of bonds by organic molecules overlapped the K^+ dispersive effect, reducing the contents of water-dispersible clay up to the estimated dose of 110 $m^3\ ha^{-1}$, from which changes could not be observed. With this change, we expect that the loss of soil particles by the action of rain and its consequent transport to water bodies will be reduced, as well as the clogging of pores in the soil by the reorganization of the dispersed clay. Therefore, vinasse can be applied to improve the physico-chemical attributes of soils degraded by annual burns.

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Compliance with ethical standards

Conflict of interest The authors declare that there are no conflicts of interest associated with this study.

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